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Project Summary

Analysis of Real-time Vehicle Hydrocarbon Emissions Data

J. Philip Childress and James H. Wilson, Jr.

Analyses using real-time dynamometer test emissions data from 13 passenger cars were performed in a study to examine variations in emissions during different speeds or modes of travel. The resulting data provided a means for separately identifying idle, cruise, acceleration, and deceleration emissions for examining how emissions differ by vehicle speed during cruise mode.

To select a set of vehicles for the study, the hydrocarbon/time relationship was established for several vehicles operating on summer-grade base fuel. Federal Test Procedure (FTP) results were then produced and examined to identify *normal* emitters (*clean* vehicles). After these vehicles were selected, an intensive analysis of their second-by-second emission characteristics was conducted.

The FTP runs for cold start, hot start, and hot stabilized emissions (Bags 1, 2, and 3 of the FTP) were performed for each of the four driving cycles—acceleration, deceleration, idling, and cruise—and the fraction of overall emissions contributed by each mode was computed for the warmed-up portion of the driving cycle. A protocol was then developed for review of the FTP real-time data.

The study results showed significant emissions differences related to travel mode: (1) cruise mode emissions are invariant with speed when expressed on a grams-per-second basis; (2) emissions resulting from acceleration from a stop to cruise speed are similar to those resulting from acceleration from cruise speed to a higher speed; (3) acceleration emissions were the highest of all the modes; and (4) cruise emissions are very similar to idle emissions.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The purpose of this project was to investigate whether it is feasible to develop new motor vehicle emission inventory procedures using *modal* (second-by-second) data, either exclusively or as a supplement to data that are more routinely collected. One issue related to the analysis is the potential for using these data to develop a future motor vehicle emissions model. At a minimum, modal emission data hold promise for validating motor vehicle emission factors.

Background

This summary presents the results of an analysis performed to examine variations in emissions during different speeds, or modes of travel, using real-time dynamometer test emissions data from 13 passenger cars. The primary data sets used for the project, developed by one of the EPA's research laboratories, included emission measurements from 1986 through 1990 model year vehicles with accumulated mileage between 17,000 and 55,000 miles.

Modal emission data, such as the data sets examined in this study, provide a means for separately identifying idle, cruise, acceleration, and deceleration emissions. These data can also be used to study how emissions differ by vehicle speed during cruise mode, which is important when trying to determine ways in which motor vehicle emissions modeling can be made simpler (such as assuming that cruise emissions per unit time are constant with speed).

It is important to note that FTP measurements are typically made in phases, or bags, and the results are expressed as averages over the measurement period. The FTP begins with a cold start, and Bag 1 represents the first 505 seconds of vehicle operation. Seconds 506 through 1372 of the FTP are known as Bag 2 and represent the hot stabilized phase of the cycle. Following Bag 2 is a 10-minute engine-off period. Then, there is a hot start and the vehicle is operated using the same speed/time trace as in Bag 1. This phase is known as Bag 3.

Procedure

The analysis described in this summary is based on work performed in two phases. Phase 1 focused on examining the hydrocarbon/time relationship for several vehicles operating on summer-grade base fuel. Overall FTP results were produced and examined to identify vehicles that had emissions that were considered *normal* (or *clean*); these were used for further analysis. For this subset of clean vehicles, hydrocarbon (HC)/time traces were developed for the long arterial road cruise section, also known as *Hill 11* of the FTP.

Phase 2 of this study involved intensive analysis of the second-by-second emission characteristics of the selected normal-emitting vehicle models. First, the reproducibility of emission patterns was examined for particular acceleration, deceleration, and cruise modes. Second, the fraction of overall emissions contributed to by acceleration, deceleration, idling, and cruise modes was computed for the warmed-up portion of the driving cycle for these modes. Finally, a protocol was developed for review of FTP real-time data.

Methodology

Phase 1:

Real-time regulated emission and fuel economy data were acquired and archived for 229 out of the 273 FTPs run during the period between January 1989 and January 1990. The real-time data included FTPs on 20 passenger cars using 13 fuels (or fuel blends) at five test temperatures, which yielded a representative cross section of emission levels.

Table 1 lists the vehicles for which emission measurements were used in this study. [Note: Because vehicle CO174G only had two FTP runs, it was not included in the data set that was analyzed for this study.] While measurements were made for the study vehicles while they were operating on a number of different fuels, only vehicles operating on summer-grade gasoline were included in this analysis. Table 2 shows the bag-specific results for each of the vehicle/run combinations where the fuel was summer-grade gasoline. While this table is useful by itself for determining the emission characteristics of the vehicles tested, these data were used primarily to identify *normal* emitters, where a normal emitter emits less than twice the applicable standard. The applicable standards for the model year vehicles tested are: 0.41 g/mi HC; 3.4 g/mi carbon monoxide (CO); and 1.0 g/mi nitrogen oxides (NO_x).

Table 2 lists selected Bag 1, Bag 2, and Bag 3 emissions for the 80 FTP runs performed using summer-grade gasoline. From this data set, 47 runs were identified as being normal emitters. It is interesting to note that of the 13 vehicles tested, 7 were *always* normal emitters, 1 was *never* a normal emitter, and the rest were normal emitters on *some* runs but not on others. It is possible that the variation in emissions between runs was caused by the temperature differences among tests and driver variability.

The FTP results were used to select two clean cars: vehicles SO756B and LS612B. The test data from these two cars were analyzed by plotting HC emissions in parts per million (ppm) versus vehicle speed (mph). One observation made from these plots was that the spikes in HC emissions relate to changes in speed (i.e., accelerations produce the highest emissions but cruise did not produce changes). It is also notable that accelerations from a cruise speed to a higher speed appear to be as important as accelerations from a stop in producing high HC emission values. Some runs show these phenomena more clearly than others, however.

Figure 1 shows the lagged 2 second acceleration (L2ACC) and instaneous hydrocarbon emission (HOTFID) variable time series for the best run of vehicle LS612B. For this vehicle, as well as for most of the "well-behaved" vehicles, the graphs of HOTFID and L2ACC show spikes in the first few seconds of positive acceleration, though they become more erratic and less prominent during other times (modes). Figure 2 plots the instantaneous HC emission rate (on a per-second basis) versus vehicle speed during cruise mode for vehicle SO756B. As the figure shows, most of the higher emission values were observed at low speeds, though the data seem to support the hypothesis that cruise mode emissions do not change much as speed increases or decreases. Other data collected in this analysis support the conclusion that cruise mode emissions are invariant with speed as well.

Phase 2:

The analyses performed for this effort were divided into three parts:

1. Standard FTP analysis for the cold start, hot start, and hot stabilized phases (Bags 1, 2, and 3) of the FTP

Table 1. *Real-Time Data Test Vehicles**

Vehicle ID	*Vehicle*	*Engine displacement (liters)*	*Accum. VIN*	*Model mileage*	*Year*
CA365B	*GM Chev. Caprice Classic*	*5.0*	*1G1BN69H9GY100365*	*39,970*	*1986*
CO174G	*GM Corsica*	*N/A*	*N/A*	*N/A*	*1987*
CO322G	*GM Corsica*	*2.0*	*1G1LT5116HY102322*	*34,364*	*1987*
CO665W	*GM Corsica*	*2.0*	*1G1LT5111JY616665*	*16,935*	*1988*
CO710B	*GM Corsica*	*2.8*	*1G1LT51W9HY104710*	*34,268*	*1987*
CV924W	*Ford Crown Victoria*	*5.0*	*2FABP73F8HX183924*	*39,242*	*1987*
ES707R	*Ford Escort*	*1.9*	*1FAPP2599HW328701*	*44,559*	*1987*
LA127B	*Chrysler LeBaron*	*2.5*	*1C3CJ41K0JG324127*	*36,418*	*1988*
LA392W	*Chrysler LeBaron*	*3.0*	*1C3XJ4538LG418392*	*20,087*	*1990*
LS612B	*GM Buick LeSabre*	*3.8*	*1G4HP14C6JH482612*	*54,802*	*1988*
SA333B	*Ford Mercury Sable*	*3.0*	*1MEBN5048HA615333*	*44,360*	*1987*
SO756B	*GM Buick Somerset*	*2.5*	*1G4NM14V7HM078756*	*45,136*	*1987*
TA207G	*Ford Taurus*	*3.8*	*1FABP524XJA148207*	*20,465*	*1988*

* Includes gasoline-fueled vehicles only. Cars listed above are those tested with summer-grade gasoline.
N/A = Data not available.

Figure 1. *HC emissions and lagged acceleration (Bag 2: 506-1006 sec; vehicle: LS612B, run: 31116).*

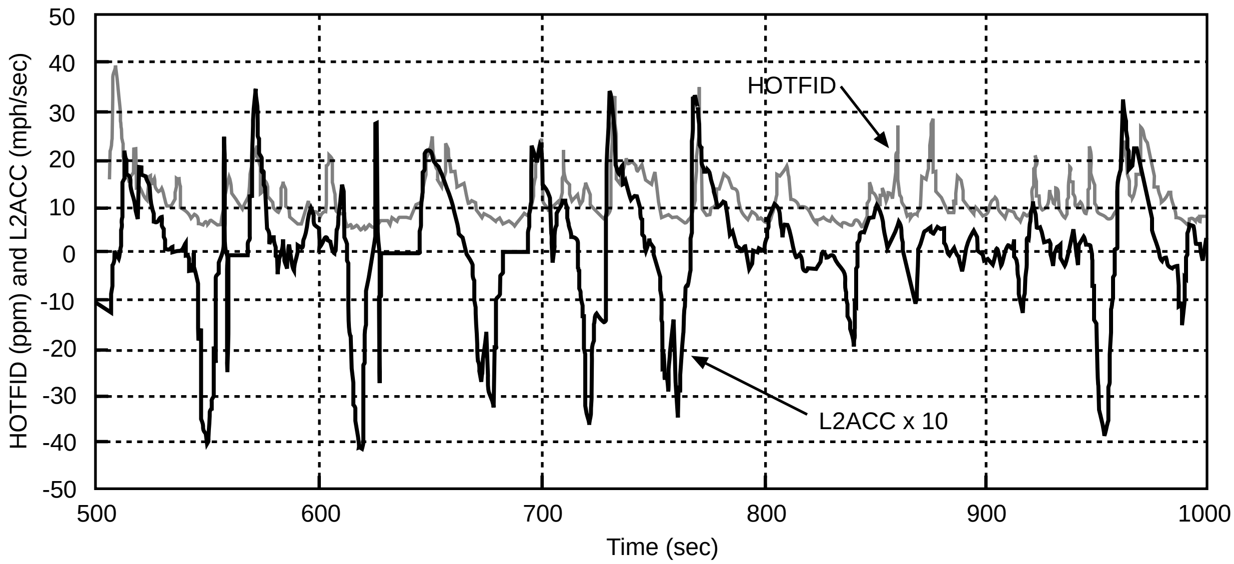

Figure 2. *Cruise mode speed vs. HC emissions (Bags 2 and 3 only; vehicle: S0756B).*

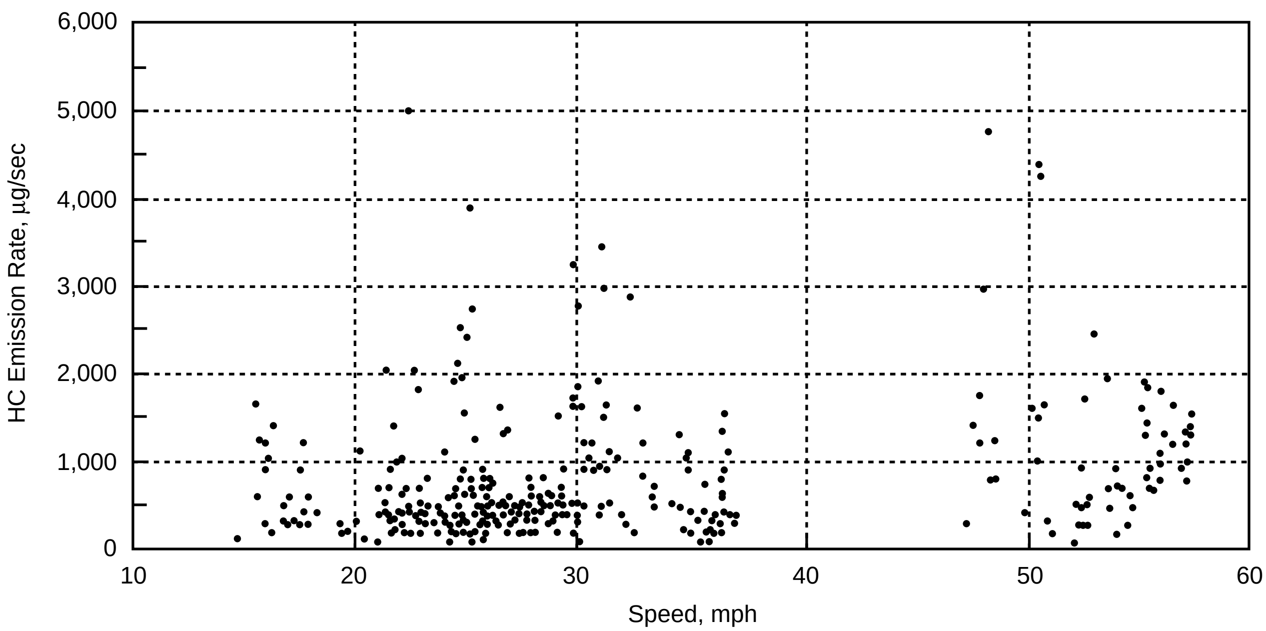

Table 2. *Weighted Bag 1, Bag 2, and Bag 3 Emissions (grams per mile)*

Vehicle ID	Run number	HC	NO_x	CO
CA365B	31065	1.47	1.13	15.32
	31061	1.47	0.89	15.80
	31060	1.33	0.83	13.42
	31057	1.28	0.76	12.75
	31063	1.69	1.06	19.94
	31062	1.39	0.99	15.16
	31064	1.77	1.18	25.17
CO174G	**31034**	**0.22**	**0.26**	**0.69**
	31036	**0.21**	**0.28**	**1.06**
CO322G	30936	0.42	0.63	8.23
	30974	0.43	1.00	10.30
	30978	0.63	2.11	15.90
	30972	0.42	0.67	8.74
	30948	**0.38**	**0.53**	**6.54**
	30945	**0.36**	**0.63**	**6.37**
	30946	0.38	0.57	7.71
	30934	**0.34**	**0.62**	**5.61**
	30975	0.45	0.90	11.15
	30973	0.42	0.69	8.73
	30971	0.43	0.73	8.80
	30935	**0.32**	**0.69**	**5.51**
	30989	0.26	0.60	7.79
CO665W	**30854**	**0.33**	**0.37**	**5.31**
	30870	0.58	0.47	11.36
	30869	0.53	0.52	10.34
	30853	**0.56**	**0.41**	**4.86**
	30861	**0.25**	**0.30**	**4.76**
	30862	**0.27**	**0.41**	**4.32**
CO710B	**30992**	**0.95**	**0.43**	**6.63**
	30999	0.85	0.41	6.23
	31002	0.99	0.37	9.45
	30996	0.88	0.37	6.06
	30994	0.92	0.36	6.35
	30997	**0.79**	**0.43**	**6.01**
	30993	1.10	0.47	6.87
	31001	0.90	0.42	7.13
	30995	**0.84**	**0.38**	**5.93**
	30990	1.15	0.42	8.39
CV924W	**31114**	**0.82**	**0.95**	**2.70**
	31107	0.91	0.85	2.85
	31106	0.86	0.87	2.79
	31115	0.95	1.01	3.09
	31113	**0.82**	**0.91**	**2.78**
ES707R	31020	0.52	0.72	11.16
	31025	0.46	0.91	12.30
	31024	0.51	0.77	13.42
	31019	0.58	0.74	12.82
	31026	**0.26**	**0.59**	**5.57**
	31021	0.54	0.80	12.27
LA127B	**31045**	**0.20**	**0.81**	**4.09**
	31042	**0.26**	**0.57**	**3.80**
	31043	**0.22**	**0.71**	**3.17**
	31044	**0.19**	**0.78**	**3.24**
	31041	**0.26**	**0.63**	**3.77**
	31046	**0.22**	**0.50**	**3.14**
LA392W	**31122**	**0.59**	**1.05**	**4.85**
	31123	**0.64**	**1.06**	**4.46**
	31124	**0.52**	**1.29**	**4.82**

(Continued)

Table 2. *(Continued)*

Vehicle ID	*Run Number*	*HC*	*NO_x*	*CO*
LS612B	***31117***	***0.31***	***0.21***	***2.26***
	31116	***0.32***	***0.18***	***2.19***
	31119	***0.28***	***0.25***	***2.12***
	31118	***0.22***	***0.18***	***1.88***
	31120	***0.31***	***0.27***	***2.71***
	31121	***0.29***	***0.26***	***2.55***
CV924W	***31114***	***0.82***	***0.95***	***2.70***
	31107	*0.91*	*0.85*	*2.85*
	31106	*0.86*	*0.87*	*2.79*
	31115	*0.95*	*1.01*	*3.09*
	31113	***0.82***	***0.91***	***2.78***
ES707R	*31020*	*0.52*	*0.72*	*11.16*
	31025	*0.46*	*0.91*	*12.30*
	31024	*0.51*	*0.77*	*13.42*
	31019	*0.58*	*0.74*	*12.82*
	31026	***0.26***	***0.59***	***5.57***
	31021	*0.54*	*0.80*	*12.27*
LA127B	***31045***	***0.20***	***0.81***	***4.09***
	31042	***0.26***	***0.57***	***3.80***
	31043	***0.22***	***0.71***	***3.17***
	31044	***0.19***	***0.78***	***3.24***
	31041	***0.26***	***0.63***	***3.77***
	31046	***0.22***	***0.50***	***3.14***
LA392W	***31122***	***0.59***	***1.05***	***4.85***
	31123	***0.64***	***1.06***	***4.46***
	31124	***0.52***	***1.29***	***4.82***
LS612B	***31117***	***0.31***	***0.21***	***2.26***
	31116	***0.32***	***0.18***	***2.19***
	31119	***0.28***	***0.25***	***2.12***
	31118	***0.22***	***0.18***	***1.88***
	31120	***0.31***	***0.27***	***2.71***
	31121	***0.29***	***0.26***	***2.55***
SA333B	***31035***	***0.39***	***1.16***	***4.42***
	31037	***0.43***	***1.23***	***4.89***
	31038	***0.41***	***1.22***	***4.77***
	31040	***0.51***	***1.49***	***6.31***
	31032	***0.39***	***1.09***	***4.91***
	31039	***0.41***	***1.52***	***6.13***
SO756B	***31017***	***0.21***	***1.06***	***2.13***
	31015	***0.19***	***1.04***	***2.00***
	31013	***0.22***	***0.84***	***2.11***
	31018	***0.20***	***1.03***	***1.95***
	31016	***0.21***	***0.98***	***1.88***
	31014	***0.24***	***0.81***	***2.19***
TA207G	***31050***	***0.51***	***0.88***	***3.04***
	31047	***0.49***	***0.75***	***2.94***
	31048	***0.43***	***0.84***	***2.85***
	31049	***0.39***	***0.79***	***2.27***

NOTES: Bold areas indicate normal emitters.

2. Modal analyses of the four driving modes within Bags 2 and 3; and
3. Statistical analysis of second-by-second HC emissions.

These analyses focused on a subset of 12 vehicles, representing 76 FTP runs, selected for data robustness (at least 4 FTP runs each), fuel (summer-grade gasoline only), and emissions behavior (showing average emissions in grams per mile of not more than twice the applicable Federal emission standard of any regulated pollutant).

Modal analysis by FTP phase for Bags 1, 2, and 3 wase performed by assigning each second of the FTP to one of four modes (idle, acceleration, cruise, or deceleration). Modes were taken from an Urban Dynamometer Driving Schedule Mode table. As a result, 81 distinct modes were identified over the complete driving cycle.

In the modal data analysis, HC emissions in grams were calculated for each of the modes of the FTP runs for the 76 FTP cases selected. In modal analysis, the concept of grams per mile is meaningless, since *speed*, or *miles traveled per second*, is used as a denominator; thus, grams per mile would be infinite in idle mode. To overcome this problem, a normalized measure of relative emissions across driving modes was developed. HC emissions were then analyzed for each of the vehicle FTP tests for the 12 vehicles studied.

Bag 3 results were selected for display because Bags 1 and 3 appear to have higher speeds than Bag 2, and there was concern that Bag 1 results might be biased by emissions in the first 100 seconds of the test (when the engine is cold). In general, emission rates for Bag 3 (in milligrams per second) are highest during acceleration and lowest during deceleration. Cruise emission rates appear to be slightly higher than those during the idle mode. Results for vehicle TA207G appear to be anomalous, since idle emission rates for that vehicle are higher than its emissions in any other mode; these results are consistent for all four test runs.

A comparison of idle emission rates among the three bags showed that, for most cars and FTP runs, the majority of the idle emissions are in the cold start mode. Of the 41 simulations with normal emission rates, the Bag 1 gram-per-second emission rates at idle are 19 times the Bag 2 rates, and 5 times the Bag 3 rates. Bag 3 idle emission rates are about twice the average Bag 2 idle emission rates.

Results

Speed Versus Emissions

The hypothesis that there is only slight correlation between instantaneous recorded vehicle speed (in miles per hour) and HC emissions rate (in grams per mile) was investigated. HC emission rate was calculated on a per-second basis, for *well-behaved* gasoline vehicles operating in the *cruise* portions of the FTP cycle. Three FTP runs per vehicle were chosen, resulting in a total of 18 FTP runs.

Only Bag 2 (seconds 506-1372) and Bag 3 (seconds 1973-2477) were used for this analysis to eliminate the potential cold start biases of Bag 1. Bag 3 is of interest because it contains highway speeds in excess of 50 mph. Hydrocarbon emissions in grams per second were calculated using a V_{MIX} number calculated from the data base for each FTP run, representing cubic feet of total diluted mix passing per second (e.g., 10.3).

No discernable correlation was found between speed and the per-second HC grams-per-mile rate. The Pearson correlation coefficients, -0.12 to -0.25 for the six vehicles, are not sufficient to indicate that a more sophisticated model could be developed to test the hypothesis.

FTP Run Statistical Analysis

Statistical analysis was also performed for 76 FTP runs covering 12 gasoline-fueled vehicles. The purpose of the analysis was to see if there appeared to be a reasonable model to use for estimating instantaneous HC emissions (HOTFID) using speed, acceleration (taken to be the first difference of speed), or lagged representations thereof. A *delta HOTFID* dependent variable was also developed, although it did not show much improvement in correlation. Only simple correlations were performed — not model regression or factor analyses.

The highest simple correlation seemed to be between the lagged (2 second) acceleration, the variable L2ACC, and HOTFID. This correlation is not consistent across vehicles, however. Nevertheless, 8 out of the 12 vehicles had correlation coefficients greater than 0.3, showing that there is a relationship between the variables (though probably a weak one).

The relationship between speed and HC emissions was further investigated for the normal emitters in the data set. This analysis was restricted to cruise mode emissions to allow full comparison of emission results, expressed on a grams-per-second basis.

Conclusions

Cruise mode emissions are invariant with speed when expressed on a grams-per-second basis. Accelerations produce the highest emissions. Accelerations from a cruise speed to a higher speed appear to be as important as accelerations from a stop in producing high HC emission values. In general, emission rates for Bag 3 (in grams per second) are highest during acceleration and lowest during deceleration. Cruise emission rates appear to be nearly the same as those during the idle mode.

J.P. Childress and J.H. Wilson, Jr., are with E.H. Pechan and Associates, Inc., Springfield, VA 22151
***Carl T. Ripberger** is the EPA Project Officer (see below).*
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